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Noise Considerations in the Design and Operation of Aircraft

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Summary

The paper is divided into two parts. The first part presents a broad view of aircraft noise problems covering the generation and transmission of noise, and the response of humans and structures to the noise. The second part, in more detail, briefly reviews the research on noise sources during the last decade and indicates the gaps which, in the author's opinion, require further work. The noise sources discussed are: propellers, inlet and exhaust of jet-engines, boundary layers, and the sonic booms.

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Symbols

a	speed of sound
A	area of jet or other aircraft noise sources
d	diameter of aircraft equivalent body of revolution
D	diameter of jet exit
db	sound-pressure level, reference 0·0002 microbar
Δdb	$20 \log_{10} p_1/p_2$
h	plate thickness
I	sound-energy flux per unit area
K_1	reflectivity factor, 1·8
K_2	volume factor
K_3	lift factor
l	length of fuselage
l_w	length of wing
M	Mach number
$\sqrt{\overline{p}^2}$	root mean square value of fluctuating pre
Δp	pressure rise at shock
P	mean pressure

q	dynamic pressure, $\frac{1}{2}\rho V^2$
R	duct outer radius
T	thrust
t	time
V	velocity
W	weight of aircraft
x	co-ordinate in stream direction
dw/dx	sound-energy flux per unit length of jet
z	height of aircraft above ground
δ^*	displacement thickness of boundary layer
η	plate damping
ρ	air density
σ	plate density
ω	frequency, radians per second
m	number of pressure lobes around circumference.

Introduction

The problem of aircraft noise has always plagued aviation. Since the development of aviation has been closely linked to military requirements, the noise has generally been tolerated in the interest of national defence. However, as military type engines were converted to commercial use, public reaction near airports required new operating procedures, possible restriction of the use of certain runways to daytime operation, and the use of jet-engine suppressors which add considerably to the expense of flight operations. At recent hearings before a Congressional Committee of the United States House of Representatives, it was estimated that the increase in fuel consumption and reduction of cruise speed caused by the suppressors resulted in a cost penalty of \$ 10,000 per month per jet airliner. The research and development cost of suppressors was estimated to be approximately 50 million dollars.

Despite this expenditure of effort and money, it has long been recognized that the jet-noise suppressor is an interim marginal solution to the problem, and that in the future noise consideration must play a major part in the design of the engines and in the matching of the engine to the airplane, so that noise may be reduced at the source without incurring such large penalties, and that the airplane has sufficient performance that it may climb more rapidly, thus reducing the noise by achieving a higher altitude near the airport. This, to a considerable extent, is being achieved through the development of fan engines which can obtain greater thrust and fuel economy with less noise.

The subject of aircraft noise involves many disciplines. With regard to noise generation there are classical acoustics, fluid mechanics, aerodynamics, and propulsion. With regard to sound transmission there are atmospheric acoustics, meteorology, architectural acoustics, and aircraft sound treatment. With regard to effects of sound on structures and man there are the fields of structural vibration and fatigue, environmental engineering, aero-medicine, bio-acoustics, and public relations.

How the many facets of the problem interact will be indicated in the first part of the paper. The second part briefly reviews the research on noise sources during the last decade. The noise sources discussed are propellers, inlets and exhaust of jet-engines, boundary layer, and sonic booms.

PART I

Relation of Source and Transmission Characteristics to Receiver Response

It is convenient to separate the subject of aircraft noise into three parts, namely, (1) the source, (2) the transmission of the sound through the air or structure, and (3) the response of the receiver. Some of the factors that must be considered in each area are presented in Fig. 1.

SOURCE	TRANSMISSION	RECEIVER
ACOUSTIC POWER	DISTANCE	STRUCTURAL FATIGUE
FREQUENCY CHARACTERISTICS	WIND AND TEMPERATURE GRADIENTS	EQUIPMENT FAILURE
CORRELATION PROPERTIES	ATMOSPHERIC AND TERRAIN ABSORPTION	HEARING IMPAIRMENT
DIRECTIONAL PROPERTIES	BARRIERS AND FENCES	DISTURBED REST
	EAR DEFENDERS	SPEECH INTERFERENCE
OPERATIONS	CHARACTERISTICS OF STRUCTURE	COMMUNITY REACTION
	FREQUENCY RESPONSE OF RECEIVER	

FIG. 1. Factors affecting the response of structures and people to aircarft noise. N.A.S.A.

A. *Source Characteristics*

The important characteristics of the source are its acoustic power, frequency characteristic, correlation properties, directional properties, and how these are affected by operating conditions. A compilation of information on jet-engine source characteristics has been made by Clark *et al.** and von Gierke. The acoustic power usually ranges from 0·01 to 0·3 per cent. of the mechanical energy of the sources for turbojets, depending on the exit velocity. Although this is only a small percentage of the mechanical energy, the larger jet-engines radiate 10–100 kilowatts of acoustic energy. The frequency characteristics are important because the transmission characteristics and response of the receiver are very frequency dependent. Most noise sources have a highly directional characteristic, with both the frequency content and magnitude of the sound pressures being a function of the direction from the source.

1. *Operational Procedures.*—The noise nuisance of an aircraft may be greatly reduced by paying close attention to operating procedures. For example, a jet-engine, in ground run-ups, should be oriented so that the maximum noise intensities are radiated into areas which have a minimum of population. Under operations one must consider also that the greatest noise is usually associated with full power and that such operations can cause hearing damage in maintenance crews and fatigue of the structure of the aircraft. Once the aircraft is airborne, operations play an extremely important role, and experience in the United States has shown that it is necessary to make certain "trade-offs" to minimize the noise nuisance. For example, for jet operation, if one holds full power in the climb-out, one may alleviate the noise problems at some distance from the airport, because the airplane will have sufficient altitude to be acceptable; however, in reaching this altitude it is likely to have created a great deal of noise nuisance near the airport. In most cases it has been found necessary to throttle back the engine and finish the climb at reduced power in order to minimize the total noise nuisance. As may be surmised, each airport will have a different problem, and the operating procedures for minimizing the noise nuisance depends on the geographic features, population patterns near the airport, the weather, and on the type of aircraft, its load and range.

B. *Transmission Characteristics*

Under transmission characteristics one considers the reduction of sound pressures that result from atmospheric propagation, the effects of barriers

* References are listed by authors in alphabetical order at the end of paper.

and various ear-protection devices, and lastly the attenuating characteristics of enclosures and the effect of frequency response of the receiver. One should attempt to make the reduction of the noise so great during transmission that it will not adversely affect the receiver.

1. *Effect of Distance, Weather and Barriers.*—Increasing the distance between the source and receiver is one of the most effective ways of reducing the transmission of the sound energy. For a homogeneous atmosphere, and if the sound is transmitted without loss, the sound energy per unit area will vary as the inverse square of the distance. This is the usual basis for estimating the effect of distance. If one speaks of sound pressure in the far field, the sound pressure varies inversely as the distance. These relations may be greatly affected by wind and temperature gradients and atmospheric and terrain absorption. These factors generally act to reduce the energy that is transmitted, although it is possible for certain weather conditions, such as temperature inversions, to lead to a greater sound intensity at a distance than one would expect from the use of the inverse square law.

Barriers, buildings, and run-up pens may be used to shield critical areas. Ear defenders and helmets are very effective means for reducing sound transmission, and the natural reaction of placing one's hands over one's ears is an effective means of saving one's hearing when exposed to intense noise.

2. *Effect of Enclosures.*—If the receiver is in an enclosure such as a building or airplane fuselage, part of the transmission path is through the structure. The transmission characteristics of the structure depend on the mass, damping, and natural frequencies of the structure as well as the absorption properties of the enclosure. The science and art of obtaining the desired sound reduction for enclosures has recently been summarized in a book by Beranek.

3. *Frequency Response of Receiver.*—Each receiver, whether it be a delicate instrument, the human ear, or part of the aircraft structures or a window in a building, has a certain frequency response characteristic which makes it sensitive to certain frequencies and nearly impervious to others. This, to a large extent, determines whether the noise will have any adverse effects on the receiver. As a matter of interest, human hearing is most sensitive in the frequency range from 500 to 5,000 cycles per second; aircraft skin structure, in the range from 100 to 1,000 cycles per second.

C. *Effect of Noise on Structures and Humans*

In the last column of Fig. 1 are listed some of the results of the noise excitation. These include structural fatigue, equipment failure, and for humans, hearing impairment in extreme cases. For the community, disturbed rest, speech interference, etc., which may lead to community reaction.

1. *Sonic Fatigue.*—Fatigue failure of skin panels, stringers, fixture brackets, and accessories of aircraft has become a common occurrence. In fact, a few hours of maximum-power ground-run may destroy large portions of wing, aft fuselage, and tail structure of multiengine-jet aircraft. Precaution must be taken to design the structure for high-intensity noise and to keep full-power ground-run to a minimum, unless precautions are taken to protect the structure. High-intensity noise has also caused malfunction of vital control equipment in aircraft and missiles. Time does not permit discussion of sonic fatigue, an area that has been the subject of intensive investigation by the airframe manufacturers and N.A.S.A. in the United States and Professor Richards' group at the University of Southampton in England. A few references are included in this paper. Of particular importance is a conference report (edited by Trapp and Forney) on the subject, which includes approximately 20 papers. A few additional papers listed include the work of Miles, Hess *et al.* and Valluri.

Repeated exposure of personnel to long periods of high-intensity noise may result in partial hearing loss. To guard against this it is necessary to provide protective devices such as ear muffs, and to take frequent hearing tests on the subjects in order to screen out any persons who may be suffering hearing impairment.

2. *Community Reaction.*—The last three items under receiver response deal with the community aspects of the noise problem. These items involve not only the physiology of noise but to a considerable extent the psychology of community reaction to the noise situation. Such elements as annoyance, fear of falling aircraft, degradation of property values, and community motivation and organization are all factors. In dealing with the community problem it is important to emphasise that the noise levels in the community are not high enough to cause damage to the hearing or to the property. In spite of the many intangible elements of the community problem, it has been possible to make some predictions as to community response to noise situation and to develop criteria for acceptable noise levels. A major part of this work has been done for the New Port Authority by Kryter of the consulting firm of Bolt Beranek and Newman, Cambridge, Massachusetts. In many cases, good public relations and education of a community with regard to the noise problem have markedly increased a community's tolerance to noise.

PART II

Research on Noise Sources

In the previous section of the paper the relation of sound source to receiver response has been discussed in very broad terms. In this section the physics of noise generation will be presented in more detail and the results of research during the last decade will be reviewed briefly for the major sources of aircraft noise.

A. *Basic Acoustic Sources*

To understand the mechanism of aircraft noise generation and to calculate the characteristic radiation patterns of the noise field, it is convenient to represent the aircraft noise source by a distribution of basic acoustic sources. These basic acoustic sources are the point source and the dipole. These have been used in acoustics over the last hundred years. More recently, Lighthill in his analysis of jet noise has suggested the use of the quadrupole.

Some illustrations of the far-field characteristics of the basic sources are given in Fig. 2 (from Hubbard and Regier). The first column gives the

SOURCE TYPE	SOURCE NAME	REPRESENTS CHANGE	RADIATION PATTERN	RELATIVE ACOUSTIC EFFICIENCY	SOUND ENERGY FUNCTION OF
	SOURCE	VOLUME		1	$\rho AV^3\left(\frac{V}{a}\right)$
	DIPOLE	FORCE		1/13	$\rho AV^3\left(\frac{V}{a}\right)^3$
	QUAD-RUPOLE	SHEAR		1/1,000	$\rho AV^3\left(\frac{V}{a}\right)^5$

FIG. 2. Properties of acoustic sources (Hubbard and Regier). N.A.S.A.

pictorial representation of each of the acoustic sources; the third column gives the type of phenomena represented. The source is used to represent the noise associated with a fluctuating volume; examples are: exhaust from reciprocating engines, pulse jets, gun blasts, and the starting of afterburners on jet-engines. The dipole is usually used where there is no fluid injected into the air, but there is a fluctuating force; examples are: propeller noise, jet-engine inlet noise, vortex noise, and boundary-layer noise, although the latter is somewhat controversial. As mentioned earlier, the quadrupole was suggested by Lighthill to explain the mechanism of noise generation of a turbulent jet of fluid. In this case, there is a great deal of noise generated even though there is no unsteadiness in the fluid injection rate and no external force fluctuations. Lighthill, therefore, described the basic mechanism in terms of quadrupole radiation. He indicates, however, that the fluctuating pressures in the turbulent field of the jet may be represented by simple sources and the fluctuating shearing stresses may be represented by lateral quadrupoles.

The radiation patterns of the various sources are given in the fourth column. The radiation patterns are often the key to the basic mechanism, and help to explain why aircraft noise sources have certain directional patterns. It should be noted that, when the sources are placed in motion, or when the aircraft source is represented by a complex array of basic sources having particular phase relations, the radiation pattern and intensities are greatly modified.

The fifth column gives the relative acoustic efficiencies for a sphere oscillating in a manner to represent the basic sources. These are selected from some values calculated by Stokes for a condition that the wavelength is twice the sphere circumference.

The last column of Fig. 2 relates the sound energy to the kinetic energy and Mach number of the aircraft noise source. These relations are derived from the far-field terms of the source equations and on certain simplifying assumptions relating the area and velocity of the aircraft source to the volume flow and frequency of the basic source.

An inspection of the last column shows that the sound energy varies as increasing powers of the velocity as the source becomes more complex, and Lighthill's V^8 is evident for the quadrupole. Experience has shown that a single source or multiple sources in random phase seem to follow the trends with velocity shown in the last column. When the sources are moving at high velocity or are not of random phase, the sound energy follows different laws.

B. *Propellers*

The main source of noise for propellers is the steady lift forces on the blades. The theory for the noise due to these steady lift forces is given by Gutin. He represented the propeller by a ring of force dipoles at the 0·7–0·8 propeller radius, the thrust dipoles being alined with the propeller axis and the torque dipoles being perpendicular to the axis. The pressures of these dipoles are integrated over the ring, and he obtained solutions of the problems in terms of Bessel functions. The results of this analysis have proved quite satisfactory in explaining the directional properties, frequency content, and effect of operating conditions, even to tip speeds in the transonic speed range. There is some indication that at the higher speeds the effect of blade thickness, which may be represented by simple source distributions (*see* Deming and Diprose), and the wave drag of the propeller may be important.

The general theory, including both the near- and far-field noise for the propeller at subsonic flight speeds is given by Garrick and Watkins. By using high-speed computing machines it is now practical to represent the propeller with a more detailed dipole distribution, taking into account both the blade chordwise pressure distribution and blade radial load distribution (Watkins and Durling). A general summary on propeller noise has recently been prepared by Regier. This includes a detailed discussion of synchrophasing, a technique for locking the propellers in such phase as to minimise the vibration levels and noise in the fuselage. Results of flight measurements and a discussion of the techniques for synchrophasing are given by Splathoff and by Piersol.

C. *Jet-Engine Inlet Noise*

The main sources of noise of jet-engines are the compressors or fans, usually referred to as inlet noise, and the turbulence in the mixing region of the free jet, usually referred to as exhaust noise. When jet-engines were placed into commercial operation, the emphasis was on the reduction of the exhaust noise, which is the main source of noise during the climb-out of the aircraft. Little attention was paid to the inlet noise, which is the main source of noise during the landing approach. An analysis of complaint patterns near large airports has shown that there are probably more complaints arising from aircraft approaches than from climb-outs, and hence the inlet noise problem is of greater importance than first anticipated. With the change-over from conventional jet-engines to fan jet-engines, the inlet noise problem has been aggravated because more energy is going into fan noise and relatively less into the jet noise.

Perhaps a word of explanation about the fan engine is in order. As indicated in Fig. 2, for jet noise (quadrupole radiation) the sound energy varies as ρAV^8. The thrust (T) of a jet-engine varies as ρAV^2; hence the sound energy varies as TV^6. Thus, for a given thrust a large noise reduction may be achieved by decreasing the jet velocity. As the velocity is decreased, the mass flow must be increased to maintain thrust. This increase in mass flow has been achieved by pumping some of the air around the engine, using shrouded fans at either the front end or at the rear of the engine. (*see* Fig. 3). Recent engines of this type built in the United States are usually called fan engines. Recent trends are to increase the ratio of bypassed air so that the air bypassed is nearly twice the air going through the turbine (*see* Gordon).

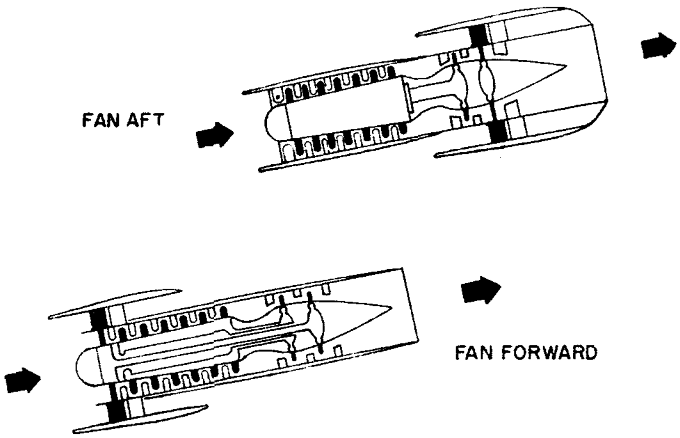

Fig. 3. Turbofan engine. N.A.S.A.

1. *Theory of Ducted Fan and Compressor Noise*.—The mechanism of noise generated is similar to that of the propeller, execpt that the unsteady blade forces play a more important role. These unsteady forces are of two kinds: (1) Periodic frequency forces resulting from stator interaction, strut interference, or non-uniform inflow. (2) Random frequency forces caused by vortex shedding, flow separation, and stalling. The periodic forces and the steady forces on the rotor blades lead to noise of discrete frequencies, at the blade passage frequency and harmonics thereof. The random frequency forces lead to a broad band spectrum, often called vortex noise.

Although the theory of noise generation for propellers has a direct application to ducted fans, the radiation characteristics are greatly modified by the transmission characteristics of the duct. The theory of noise transmission in ducts is well established. Only recently, however, has a co-ordinated theory for the noise from ducted fans been given, which considers both the generating mechanisms and the transmission characteristics. It is believed that this theory proposed by Tyler and Sofrin presents the framework for understanding compressor noise, and eventually should lead to more refined methods for quantitatively calculating the noise intensity of compressors and fans. The theory treats the propagation of the steady and the periodic blade loads through ducts having various ratios of inside to outside radii, and gives the spatial radiation pattern from such ducted rotors.

Tyler and Sofrin have calculated the duct transmission loss for the steady pressures on the blades for various rotor configurations. A typical example of some of these calculations is shown in Fig. 4. This presents the loss, expressed in decibels per outer radius of duct length as function of rotor tip Mach number. In this example, the inner duct is one-half the outer duct radius. The different curves are for different number of lobes in the rotating pressure field. For example, $m = 32$ would represent the fundamental frequency due to the steady loads on a 32-blade rotor.

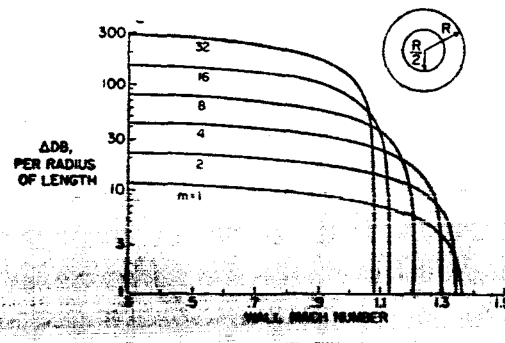

FIG. 4. Cylindrical duct decay rates. (Tyler and Sofrin, Pratt and Whitney Aircraft Corp.) N.A.S.A.

A word of explanation about decibels may be in order. In this figure $\Delta db = 20 \log_{10} p_1/p_2$ where p_1 is the fluctuating pressure at the rotor and p_2 is the fluctuating pressure in the duct one radius from the rotor. Thus, at $\Delta db = 20$ the pressures have dropped to 1/10 and at $\Delta db = 100$, the pressures have dropped to 10^{-5}.

It may be noted that the pressures become insignificant at subsonic tip speeds, particularly for the higher values of m, but for supersonic speeds the pressures are propagated without loss. There is still some loss at low supersonic speeds, because part of the rotor may be subsonic near the hub when it is supersonic at the tip.

The stator interaction results in pulsing pressure fields which are fixed in space. In the Tyler-Sofrin theory the pulsing pressure field of the stator is resolved into an infinite series of rotating pressure fields of constant amplitude, having rotation in the same and opposite direction as that of the rotor, and rotating at speeds greater and less than rotor speed. It turns out for most practical situations and some of these rotating fields will have supersonic speeds even though the rotor is subsonic. Hence, these modes will be transmitted through the duct without loss. The theory thus shows for subsonic rotor speeds that the noise due to the steady forces is attenuated in the inlet duct, but that the noise due to the unsteady loads is difficult to attenuate in the duct.

2. *Experiments on Compressor Noise.*—The theory given in the preceding section has dealt with the steady and periodic forces on the blade. In practice, it has been found that much of the compressor noise comes from the random forces on the blade, and that the noise spectrum is very broad. An example of the noise spectra of a single-stage rotor driven by an electric motor is given in Fig. 5. These are some results of an investigation being

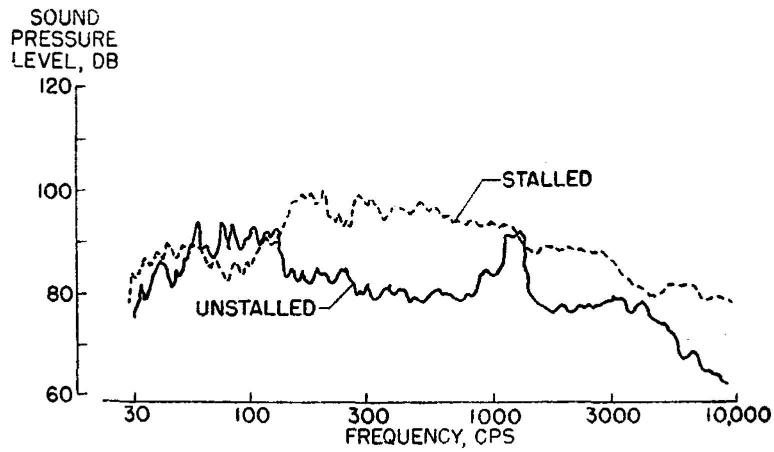

FIG. 5. Comparison of one-third octave band spectra for stalled and unstalled rotor (Modlin). N.A.S.A.

conducted at N.A.S.A., Langley Research Center, by C. T. Modlin. In Fig. 5 the one-third octave pressure levels are plotted as function of frequency for normal operating conditions and for the rotor stalled. For the rotor in normal operation one may note a random output that peaks at low frequencies, and a spike in the curve slightly above 1,000 cps. This spike represents the rotor fundamental frequency and is due to the periodic loads. Since the ear has its maximum sensitivity in the range where the fundamental rotor frequency usually occurs, most persons find this discrete frequency very objectionable. In fact, the ear will often sense the discrete frequencies of the compressor noise, even though the frequencies are not discernible in an octave band analysis of the noise. These discrete frequencies are, however, easily detectable with a narrow band analyzer. For noise of this type, Little shows that a 1/24 octave band analysis indicates a 10-decibel spike in the spectrum, whereas the octave band analysis shows only a broad spectrum. It is generally recognized that methods for predicting perceived loudness which are based on octave band data are not applicable to noises having a discrete high-frequency component and a re-evaluation is now being made of the methods.

As the rotor is stalled, one notes in Fig. 5 a large increase in the broad random noise and the discrete frequency noise is submerged in the random noise. Some indication of the spatial distribution of the noise and the effect of mass flow on the intensity of the noise is given in Fig. 6. The rotor speed was held constant and the mass flow was changed by choking the exit. It may be noted that the noise is a minimum at some intermediate mass flow and is about 8 decibels higher in the stall.

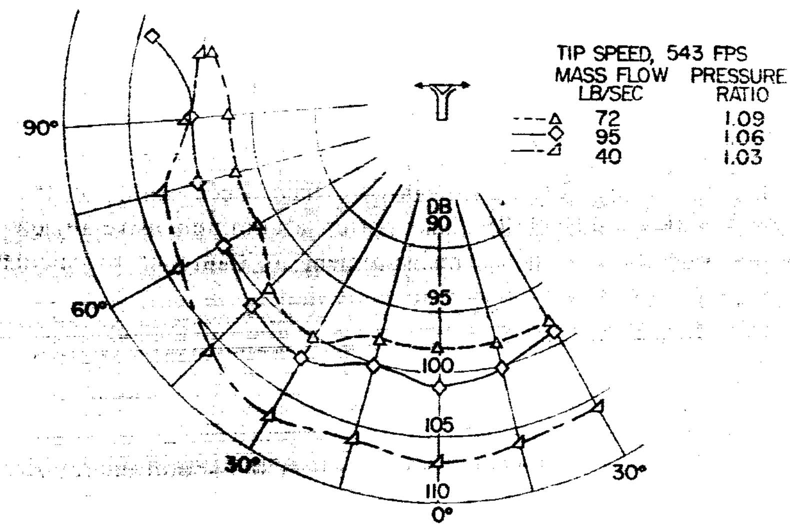

FIG. 6. Effect of rotor load on the overall noise levels (Modlin.) N.A.S.A.

Greatrex presents flight and ground-run measurements of the compressor noise of various engines and presents semi-empirical relations for predicting the white random noise and the discrete frequency noise of compressors. Some results are also given on the use of a choked (sonic) inlet to eliminate the noise. The sonic inlet is a very effective way of eliminating inlet noise; however, the problem of providing a fail-safe choking device and the mechanical complications of such a device have prevented its use for current aircraft.

A recent article by Gordon reviews some of the work done in reducing the noise of an aft-fan jet-engine. In this engine the discrete frequency noise was radiated mainly in the aft direction. Resonator type sound absorbers are used in the exhaust nozzle to reduce the discrete frequency noise in this engine.

Although the fan engine noise problem remains one of considerable concern, recent research has thrown light on the mechanism of noise generation and propagation and various means have been found to reduce the intensity of the noise. Some of these methods include cleaning up the flow into the rotor, increasing the distance between stators and rotors, changing the stage loading, and using sound absorbers in the duct.

D. *Jet Exhaust Noise*

1. *Theory.*—This is a subject that has been intensively studied in recent years, and some information on this subject is given in previous sections of this paper. In this section we shall give only a very brief coverage of the subject. Most theoretical investigations start with Lighthill's classic work, in which he presents the inhomogeneous wave equation and shows that any turbulent field is equivalent acoustically to a distribution of quadrupoles of strength T_{ij} placed in a uniform medium at rest. Ribner, Mollo-Christensen and Narasimha, Lilley, Dyer and Powell have been some of the recent investigators in this field. Lilley has written a comprehensive review paper in which he used the turbulence measurement of Laurence to calculate the noise sources distribution in a jet, and finds that the main source of noise is the shear-turbulence interaction which exists in the mixing region of the jet, namely, in the region of the jet from the exit to approximately 6 diameters downstream. Similar results have also been found by Ribner and others, who show that the energy radiated per unit length of jet in the mixing region is a constant, and that in the fully developed jet the sound energy drops off as the x^{-7} power of the distance. This is illustrated in Fig. 7.

2. *Experiment.*—Experimental work on jet noise has been extensive, starting with the early work on model jets by Westley and Lilley, and Lassiter and Hubbard, to full-scale work on jets by Howes *et al.*, and Callaghan and Coles. A large amount of work, particularly with hot jets, has been done by engine and airframe manufacturers in both England and the United States. A recent summary of jet noise work is given by Howes. These studies have, in general, confirmed the scaling laws indicated by the theory, and shown that the sound power varies approximately as the velocity to the eighth power for subsonic jet speeds. As the velocity is increased to supersonic speeds, the sound power no longer varies as the eighth power, but more nearly as the third power of the velocity, the sound power being approximattely $\frac{1}{2}$ to 1 per cent. of the mechanical energy of the jet (*see* Mayes and von Gierke). This behaviour of the supersonic jet may be explained in part by the fact that little noise seems to originate from the supersonic flow, and the center of noise

emission appears to be in the region where the jet shocks down to subsonic speed, several jet diameters behind the jet exit.

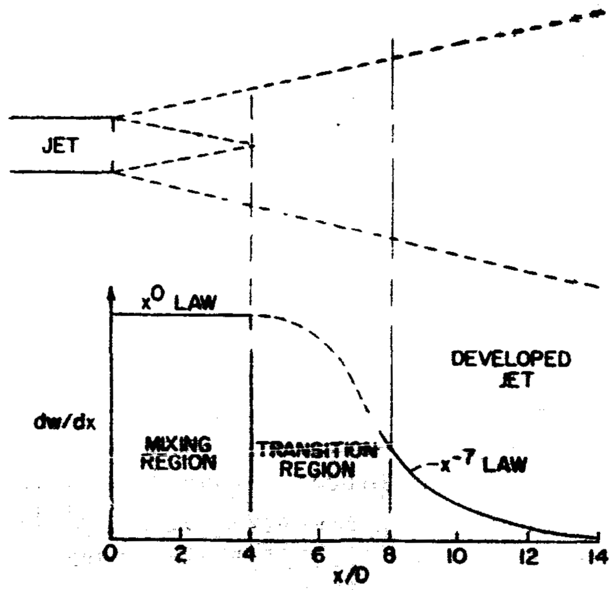

FIG. 7. Theoretical noise energy distribution from jet exhausts (Ribner). N.A.S.A.

3. *Noise Suppression.*—Since the source of noise of subsonic jets is the mixing region (Fig. 7), jet mufflers have generally worked on the principle of shortening the mixing region by causing the rapid spreading of the jet and entrapping the ambient air into the jet, thus more rapidly reducing the velocity of the jet. Some of the practical applications and evaluation of various types of jet mufflers are given by Withington, Greatrex, Coles and Callaghan and Gordon.

Research on jet noise suppression is still continuing particularly with regard to the mixing of the hot and cold flow of the fan engines. The supersonic jet, although not of primary concern for commercial aircraft, is of major concern with regard to missiles and spacecraft launchers, and hence the subject of further study.

E. *Boundary-Layer Noise*

The increase in speed and dynamic pressure of transport jet aircraft has placed an emphasis on boundary-layer-noise investigations. This is now the principal source of fuselage noise for the high-speed subsonic jet cruise flight, and its importance will increase for the supersonic transport.

It is well to consider the boundary-layer-noise problem in two parts: (1) the magnitude, frequency content, and correlation lengths of the pressure at the boundary, and (2) the sound transmitted by a flexible wall when subjected to the boundary-layer pressure fluctuations.

1. *Experiments on Boundary-Layer Pressures.*—An excellent summary of the first part, namely, the pressure characteristic for the subsonic boundary layer is given by Willmarth. He shows for a fully developed turbulent boundary-layer that the ratio of the root mean fluctuating pressure to the free-stream dynamic pressure $\sqrt{\bar{p}^2}/q_\infty 6 \approx \times 10^{-3}$. The ratio is essentially independent of Reynolds number or subsonic Mach number. This has been borne out by flight measurements and other investigators. The measured values vary somewhat from approximately 3 to 9×10^{-3}, depending on test conditions and instrumentation. The spectral density of the fluctuating pressures is essentially flat from $\omega\delta^*/V = 0{\cdot}1$ to $1{\cdot}0$. The dropping off of the spectral density curve at the high frequencies seems to be a function of the size of the pressure sensor to the displacement thickness of the boundary layer; hence, the upper limit of the frequency is not determined.

Space-time correlation of the pressures at two points taken with variable time delay is presented in Fig. 8. This shows that the correlation of the

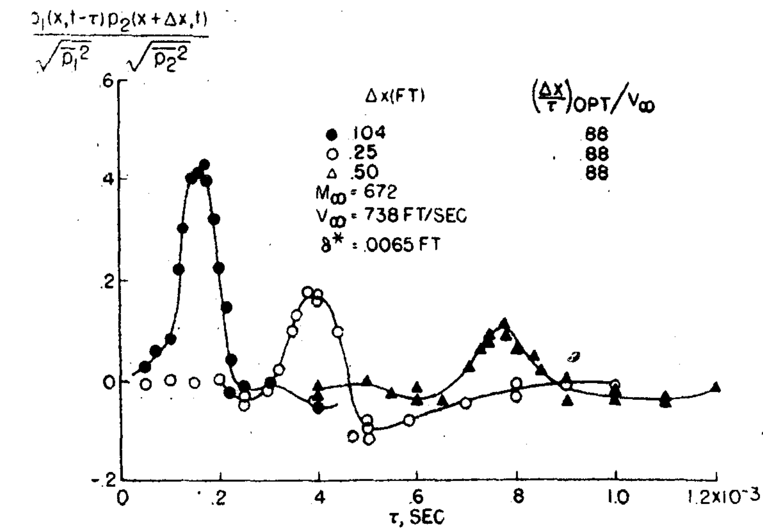

FIG. 8. Streamwise space-time correlation of wall pressures in boundary layers (Willmarth). N.A.S.A.

pressures is $0{\cdot}4$ at a distance $0{\cdot}1$ foot apart for a boundary-layer-displacement thickness of $\delta^* = 0{\cdot}0065$ foot, and that the pressure impulse seems to be convected downstream at approximately 88 per cent, of free-stream velocity. Even at a distance of 0·5 foot the correlation is still apparent, being in the order of 0·1. If the turbulence were transported as a frozen pattern, the maximum correlation would be unity independent of distance. This dying out of the correlation with distance is sometimes referred to as "melting frozen turbulence".

2. *Theory on Sound Transmitted by Flexible Wall.*—There is still considerable confusion in the prediction of boundary-layer noise inside a fuselage, and how it should vary with flight conditions and structural properties of the wall. Corcos and Liepmann have considered the case in which the fluctuating pressures are considered correlated only over a limited area, proportional to the boundary-layer thickness, but small with regard to size of plate. The pressures are assumed to act like rain on a roof. They find that under these assumptions (and an assumed flat input spectrum and thin boundary layer), the sound intensity I is given by the following proportionality

$$I \propto \frac{\rho_\infty^2 \rho_c V^5 \delta}{a_c \eta \sigma^2 h^2}$$

where ρ_∞ is free-air density, ρ_c and a_c are cabin density and speed of sound, V is the velocity, δ is the boundary-layer thickness, η is the plate damping, σ is the plate density, and h is the plate thickness. (If the sound pressures inside the fuselage were directly proportional to the boundary-layer pressures, the sound energy would vary as V^4, since $I \propto p^2$.)

Ribner has treated the same problem on the assumption that the turbulence is a frozen pattern transported over the plate. He finds that for an infinite plate, at subsonic speeds, no sound is radiated but the internal pressures die out exponentially. However, for the finite plate, reflections of the travelling waves are set up at the plate boundaries, resulting in noise radiation. He finds for thin boundary layers that the sound should vary as $(\delta/h)^3 V^5$, and for thick layers, as $V^3 (\delta/h)$. Kraichnan in the analysis of a square plate with frozen turbulence finds for thin boundary layers that the energy varies as the fourth power of the boundary-layer thickness.

The response of panels to "frozen melting turbulence" has been studied by Dyer. The correlation is assumed to die out exponentially and have a scale that is small compared to the plate dimension. He finds the effect of convection of turbulence to be small unless the convection speed approaches the speed of travelling waves in the plate, and the correlation distance is comparable to the wavelength of the travelling waves in the plate.

Previous investigations have neglected the interaction between the plate deformation and the airflow. This may not cause errors at subsonic speeds;

however, at supersonic speeds this interaction may be important. Houbolt considers the response of a plate to a frozen turbulence pattern at supersonic speed, taking account of the interaction of plate deformation and airflow. He finds that the plate response increases rapidly as the panel flutter speed is approached. This, of course, makes a large amount of noise, and pilots of supersonic aircraft have usually been able to detect panel flutter from the high noise levels.

3. *Experiments on noise due to boundary layers.*—The question of how the sound energy varies with boundary-layer thickness has not been resolved. It is a well-known fact that near the rear of a fuselage where the boundary-layer is thicker, the sound is of higher intensity and more sound-proofing is required. Sound measurements inside subsonic airplanes have confirmed that the sound energy varies as V^5.

During the development of the Mercury man-carrying space capsule, opportunity was taken to measure internal noise levels as function of dynamic pressure and Mach number. The capsule is equipped with a bridge work escape tower and the whole configuration is extremely rough. Hence, one might classify it as having a thick boundary layer. Some of the results taken from Hilton *et al.* are shown in Fig. 9. Results are given for flights

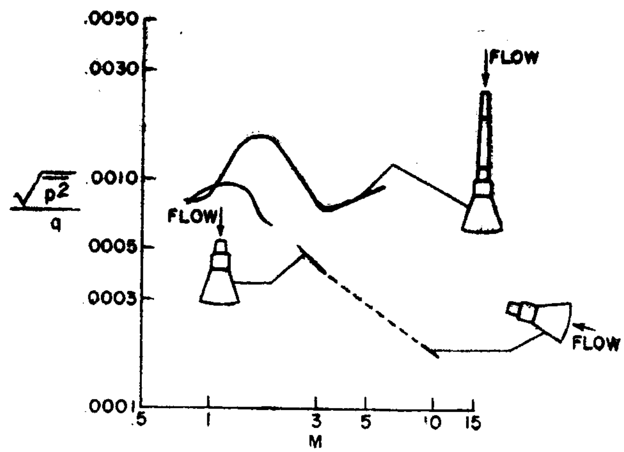

FIG. 9. Internal noise pressures in mercury capsule (Hilton, Mayes and Hubbard). N.A.S.A.

with and without the escape tower. It may be noted that the internal noise pressures for the configuration with the escape tower fluctuate somewhat erratically with Mach number, but lie in the general region of 0·1 per cent. of the free-stream dynamic pressure. The sound pressures in the capsule without the tower are lower, particularly at supersonic speeds, As indicated earlier, the question of the supersonic boundary-layer noise is of great importance, and little systematic data have been obtained. Careful experiments and further theoretical work on this speed range are needed.

F. *Sonic Booms*

There is presently great interest in the sonic boom and how it will affect the design of future commercial supersonic aircraft. An assessment of some of these factors both as to engine and aircraft configuration requirements is given by Nichols, Lilley and Spellman, and Hubbard and Maglieri. Desirable goals for both engine and aircraft are that it shall be able to land and take off from present airports without exceeding present noise levels, and that the aircraft shall be able to reach a sufficient altitude before going supersonic, so that the sonic booms created will not be objectionable.

1. *Theory for Volume and Lift Noise.*—The basic theory for the sonic boom, which relates the geometry of the aircraft to the sonic boom pressures on the ground, is given by Whitham. In this theory the linearized solution for the characteristics of a slender body of revolution are modified to account for the fact that the pressures are not propagated as Mach waves at the speed of sound in the undisturbed medium, but at speeds that are a function of the shock strength. Although the theory deals specifically with bodies of revolution, in application of the theory to aircraft, the aircraft is treated as a body of revolution having the same cross-sectional area as the aircraft. This noise due to the volume of the aircraft is for present-day aircraft, the main source of sonic boom noise, and has lately been termed volume noise, to distinguish it from the noise due to the weight of the aircraft which is usually termed lift noise.

The theory for the lift noise was developed nearly concurrently by the Manchester group in England, and by Busemann of N.A.S.A. A graphic mechanical analogy taken from Busemann is presented in Fig. 10, in which the supersonic airplane is illustrated as being carried by a lifting crowbar. Since the ground reaction is behind the airplane, the lift of the airplane must be carried as a force and a moment. For flight at high altitudes the ground pressures due to the moment are many times those due to the force, and hence the N type pressure signature for the lift noise is similar to that for volume.

Since the propagation of shocks from the aircraft is a non-linear problem, it is necessary to combine both the lift and the volume noise at the aircraft, rather than add their contribution in the far field. The theory for the combined noise has been treated by Walkden, and application of this method has been made by Morris, Carlson, and others, both in government and industry. These theoretical studies show how the position of the wing affects the intensity of the bow shock. The most favourable position of the wing is near the rear of the fuselage, where the positive pressure field under the wing is partially cancelled by the negative pressure of the fuselage. With a wing so placed, at low altitudes the lifting surface makes no contribution to the bow shock; however, at high altitudes, the volume effects and fuselage pressures become so low that the lifting surface is the main source of the sonic boom.

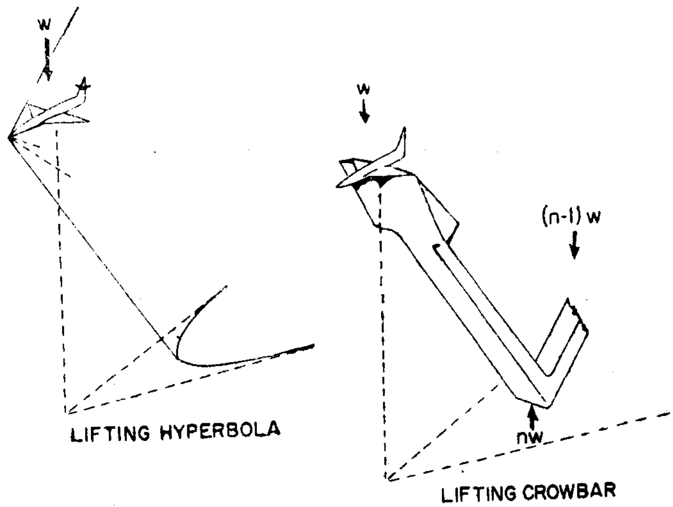

FIG. 10. Pressure on ground due to weight of airplane (Busemann). (From *Proceedings of Conference on High Speed Aerodynamics, Polytechnic Institute of Brooklyn*, January 1955. Permission for use granted by Polytechnic Institute of Brooklyn). N.A.S.A.

Although the ground shock pressures are determined by combined volume and lift effects, it is of interest to look at the far-field equations for each component separately. The following equations are taken from a report by Maglieri and Hubbard. The equation for the pressure on the ground due to volume only is

$$\frac{\triangle p_V}{P_0} = K_1 K_2 \left[\frac{P_a}{P_0}\right]^{\frac{1}{2}} (M^2 - 1)^{\frac{1}{8}} \left(\frac{d}{l}\right) \left(\frac{l}{z}\right)^{\frac{3}{4}}$$

where $\triangle p_V/P_0$ is ratio of the bow shock pressure to ambient, K_1 is taken as 1·8 to account for ground reflection, K_2 is a form factor taken as 0·62 for a particular test airplane, P_a and P_0 are the atmospheric pressure at the airplane and ground level, respectively, d is maximum diameter of body of revolution representing the airplane, l is the length, and z is the altitude. Lansing has explored the range of the form factor K_2 for a number of current aircraft and arbitrary bodies of revolution. He finds the value of K_2 to vary from 0·57 to 0·64 for airplanes, and from 0·54 to 0·8 for extreme ranges of an arbitrary shape.

The equation for the lift noise is

$$\frac{\Delta p_L}{P_0} = K_1 K_3 \frac{(M^2 - 1)^{\frac{1}{8}}}{M} \left(\frac{W}{P_0 l_w{}^2}\right)^{\frac{1}{2}} \left(\frac{l_w}{z}\right)^{\frac{3}{4}}$$

where W is the weight of the aircraft, and l_w the length of wing projection on centreline and $K_3 \approx 0 \cdot 60$ for a delta wing airplane. Morris has explored the range of K_3 for various lift distributions and finds it to lie between 0·5 and 0·7.

An inspection of the two equations shows that for the volume noise the ratio of shock pressure to ambient ground pressure is reduced by the factor $(P_a/P_0)^{\frac{1}{2}}$ in addition to the explicit distance factor $z^{-\frac{3}{4}}$. The ratio $(P_a/P_0)^{\frac{1}{2}}$ does not appear in the lift formula. Hence, as altitude is increased the volume noise decreases much faster than lift noise. The reason for this is that the airplane weight must still be supported by the ground regardless of altitude of the airplane; however, the strength of shocks due to volume is a function of the air density at flight altitude.

2. *Experiments on Steady-Flight Sonic Booms.*—A considerable amount of flight data on sonic boom pressures has been accumulated. Some of this is shown in Fig. 11 taken from a paper by Maglieri and Hubbard. This

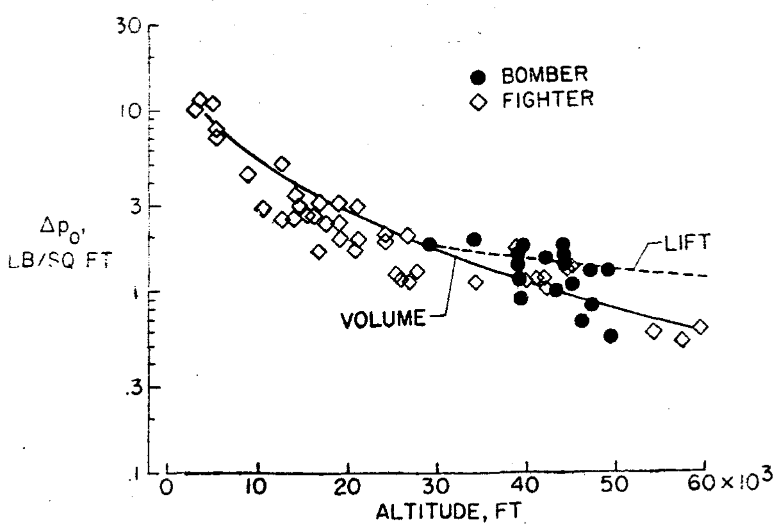

FIG. 11. Sonic boom pressures for fighter and bomber-type aircraft. All data have been normalized by volume equation to $l = 100$ feet, $M = 1 \cdot 6$, and $l/d = 9$ (Maglieri and Hubbard), N.A.S.A.

includes both fighter and bomber data; the pressures for the fighter aircraft have been adjusted to the size of the bomber by use of the relations of the equation for volume noise. The data, in general, follow the theoretical trend, except that the bomber data on the average are a little above the theoretical line, indicating that there may be some lift noise in the bomber data. The theoretical lift curve for the maximum weight condition for the bomber is shown by the dashed line.

3. *Effect of Aircraft Manœuvres.*—The discussion thus far has dealt with the sonic boom in steady level flight in a homogeneous atmosphere. As was shown by Prandtl and others, the acceleration of a supersonic vehicle (whether the acceleration be linear or due to curvature of the flight path) produces cusps in the shock front, and regions of high-intensity shocks. These shocks are sometimes referred to as superbooms. This is illustrated in Fig. 12 taken from a recent study by Lansing. In this figure the airplane

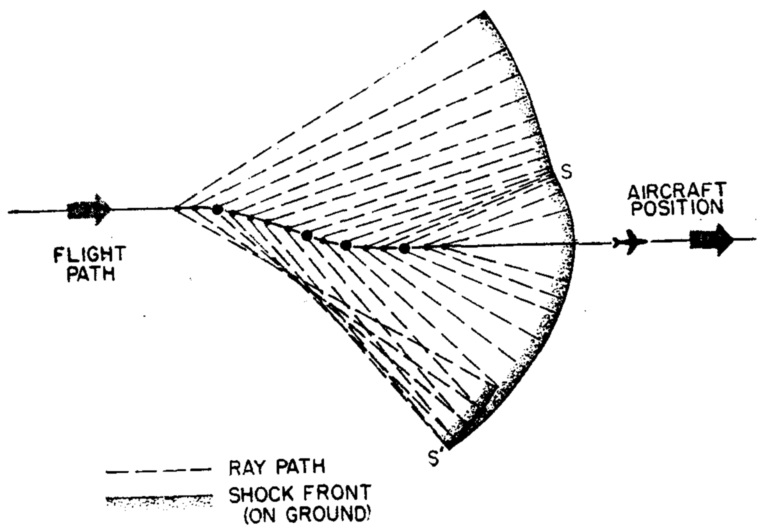

FIG. 12. Ground shock wave showing formation of cusps and foci (Lansing). N.A.S.A.

is flown at 30,000 feet in a manœuvre which displaces its path 3 miles, while travelling a distance of 14 miles. As Rao shows, the shock-front energy between any two rays remains a constant (except for the shock losses). Hence, if the rays spread apart, the shock becomes weaker, and if the rays converge, the shock is intensified. Thus, at regions S there are foci of the rays which result in an intensification of the shock, and at S′ there is a cusp, also with a shock intensification. Rao has presented a method, based on Witham's non-linear theory, for predicting the intensity of the shocks in these regions, and in general for any accelerated flight. Randall has applied this method to calculate the intensity of sonic booms for various manœuvres, and has also shown very important effects of temperature and wind gradients in the atmosphere on the extent of the sonic boom corridor on the ground.

In summary, it would appear that the theory for the sonic boom is fairly complete, and will probably stand unless more refined flight measurements show significant discrepancies. The main problems that remain deal with evaluating the lift noise of very large airplanes, determining the sound propagation from extreme altitudes, determining effects of the non-homogeneous atmosphere, meteorological conditions, and normal flight manœuvres on the intensity of the boom.

Concluding Remarks

We have attempted to present a brief survey of some of the noise problems of the last decade and some of the results of research on noise sources that are of current interest. As the speed of commercial aircraft is increased to supersonic speeds, the old problems as well as new problems, such as the sonic boom, are factors that must be given careful consideration in the design and operation of such aircraft.

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